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Climate change impacts on life cycle greenhouse gas (GHG) emissions savings of biomethanol from corn and soybean

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Abstract
Purpose The purpose of this study is to assess and calculate the potential impacts of climate change on the greenhouse gas (GHG) emissions reduction potentials of combined production of whole corn bioethanol and stover biomethanol, and whole soybean biodiesel and stalk biomethanol. Both fuels are used as substitutes to conventional fossil-based fuels. The product system includes energy crop (feedstock) production and transportation, biofuels processing, and biofuels distribution to service station.
Methods The methodology is underpinned by life cycle thinking. Crop system model and life cycle assessment (LCA) model are linked in the analysis. The Decision Support System for Agrotechnology Transfer – crop system model (DSSAT-CSM) is used to simulate biomass and grain yield under different future climate scenarios generated using a combination of temperature, precipitation, and atmospheric CO_2. Historical weather data for Gainesville, Florida, are obtained for the baseline period (1981–1990). Daily minimum and maximum air temperatures are projected to increase by +2.0, +3.0, +4.0, and +5.0 °C, precipitation is projected to change by ±20, 10, and 5 %, and atmospheric CO_2 concentration is projected to increase by +70, +210, and +350 ppm. All projections are made throughout the growing season. GaBi 4.4 is used as primary LCA modelling software using crop yield data inputs from the DSSAT-CSM software. The models representation of the physical processes inventory (background unit processes) is constructed using the ecoinvent life cycle inventory database v2.0.
Results and discussion Under current baseline climate condition, net greenhouse gas (GHG) emissions savings per hectare from corn-integrated biomethanol synthesis (CIBM) and soybean-integrated biomethanol synthesis (SIBM) were calculated as −8,573.31 and −3,441 kg CO_2-eq. ha^{-1} yr^{-1}, respectively. However, models predictions suggest that these potential GHG emissions savings would be impacted by changing climate ranging from negative to positive depending on the crop and biofuel type, and climate scenario. Increased atmospheric level of CO_2 tends to minimise the negative impacts of increased temperature.
Conclusions While policy measures are being put in place for the use of renewable biofuels driven by the desire to reduce GHG emissions from the use of conventional fossil fuels, climate change would also have impacts on the potential GHG emissions reductions resulting from the use of these renewable biofuels. However, the magnitude of the impact largely depends on the biofuel processing technology and the energy crop (feedstock) type.

Keywords Biodiesel · Bioethanol · Biomethanol · Climate change · DSSAT-CSM · GaBi 4.4 · GHG savings · LCA (life cycle assessment)

1 Introduction

Climate change is one of the major problems facing the world today and has been attracting scientific and political concerns both nationally and internationally. Consequently, anthropogenic climate change has been exerting global scale impacts

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on our environment, and agricultural crops production is considered one of the most vulnerable sectors to these potential consequences due to its inherent sensitivity to climate variability and change (Fischer et al. 2002; Gornall et al. 2010; Müller et al. 2011). Thus, climate change, as predicted by the Intergovernmental Panel on Climate Change (IPCC 2007a, 2007b), has the potential to significantly impact global production of biofuels, since biofuel production hugely relies on production of dedicated energy crops (Sims et al. 2006). Climate change, as projected to continue throughout the century, is generally expected to have detrimental effects on agriculture causing a considerable variation in crop yields, even under a moderate air temperature increase of 1–2 °C (IPCC 2007a, 2007b; Berg et al. 2013; Teixeira et al. 2013). This is an additional challenge to the global biofuels production system from agricultural energy crops which is already facing numerous challenges such as efficient conversion technologies, land use requirement, and competition with food and nature (Naik et al. 2010).

Biofuels are renewable energy sources processed from biomass and can be produced from agricultural products such as dedicated energy crops and agricultural residues with the potential to be used as a direct substitute for conventional fossil fuels in transport. Biofuels are considered 'carbon neutral' because they are produced within the short-term carbon cycle, and their combustion only returns as much CO_2 to the atmosphere as that is captured during plant growth. Bioethanol and biodiesel currently produced from food materials such as starch and vegetable oil, respectively, (conventional or first generation biofuels) are the most common forms of biofuel produced in many countries, including USA, Brazil, and China. In contrast, the production of second generation biofuels (e.g. biohydrogen, biomethanol, bioelectricity, Fischer–Tropsch diesel, bio-DME, etc.) from non-food lignocellulosic plant biomass has the potential to be carbon negative and to avoid the conflict between food and fuel production (Sims et al. 2010). Sustainability of a biofuel product depends on its environmental, economic, and social impacts throughout the entire life cycle of the production chain. Thus, reliable quantitative assessments of how climate change may impact the sustainability of biofuel production systems are of crucial importance. To understand the implications of climate change on production of biofuel, we need to quantify the impact that results from changes in increasing air temperatures, precipitation pattern, and increasing atmospheric concentrations of CO_2.

However, the link between climate change and biofuel production systems has attracted very little interest from policy makers and stakeholders. Few studies have been presently conducted on the impact of climate change on biofuel production systems from agricultural crops, focusing particularly on two main aims – availability of feedstock supply (Stromberg et al. 2011; Tuck et al. 2006; Wang et al. 2012) and net energy value (NEV) (Persson et al. 2009a; Persson et al. 2009b; Persson et al. 2011). Much remains to be understood regarding the potential implications of climate change on the environmental sustainability (in terms of greenhouse gas (GHG) emissions) of biofuel production systems.

In this study, we employ a robust life cycle approach that integrates climate change, crop yields, and biomethanol net greenhouse gas (GHG) emissions savings. Crop system models (CSM) linked to life cycle assessment (LCA) models are used to predict biomethanol net GHG emissions savings from corn and soybean as a function of climate change. The Decision Support System for Agrotechnology Transfer (DSSAT-CSM) crop systems software which simulates crop yields such as cereals (barley, maize, millet, sorghum, rice, and wheat), legumes (soybean, cowpea, peanut, chickpea, dry bean, and velvet bean), root crops (cassava, potato, and taro), etc. was used to project the impacts of changing climate on yields of corn and soybean, grown on marginal land. We analyse the combined effects of increasing air temperature, changing precipitation patterns, and increasing atmospheric levels of CO_2 on yield projections. Yield outputs from the DSSAT-CSM model are used as inputs into GaBi v4.4 LCA model software (PE). This allows us to calculate the potential GHG emissions savings of biomethanol production systems as affected by climate change, when biomethanol is used as a substitute to conventional fossil-based gasoline. Bioethanol that is co-produced from corn biomethanol synthesis system is used as replacement to fossil-based gasoline, while biodiesel, another co-product of soybean biomethanol synthesis system, is considered as replacement to fossil-based diesel.

2 Methodology

The methodology is underpinned by life cycle thinking. Crop system models (CSM) – DSSAT-CSM v4.0.2 – and LCA models – GaBi v4.4 – were integrated and used as tools for assessing the carbon footprint of whole corn bioethanol and stover biomethanol and whole soybean biodiesel and stalk biomethanol when they are used as alternatives to conventional fossil-based fuels.

2.1 Crop models and inputs

Corn and soybean dry biomass yields (grain/seed and stover/stalk) were simulated for baseline (control) and projected climate change scenarios and used as inputs into the LCA analyses. Process-based crop model simulations were run with the CERES-Maize (Ritchie et al. 1998) and CROPGRO-Soybean (Jones et al. 2003) of the DSSAT-CSM model v4.0.2 software

(Hoogenboom et al. 2003) for corn (*Zea mais L.*) and soybean (*Glycine max*), respectively. The models simulate physiological crop responses on a daily basis as a function of climate factors (daily maximum and minimum temperature, precipitation, and solar radiation), soils, and crop management practices (cultivar, planting date, row spacing, plant population, and planting depth). The models have been applied extensively in many different parts of the world for climate change applications (e.g. Gungula et al. 2003; Rötter et al. 2012; Eyshi-Rezaie and Bannayan 2012). Gainesville, Florida, USA, meteorological weather station data were used in the study because of readily available and reliable data in a suitable format required by the DSSAT-CSM model.

The CERES-Maize is a predictive and deterministic model of the DSSAT model. The model is designed to simulate corn growth, soil, water, temperature, and soil nitrogen dynamics on a field scale for one growing season and belongs to the same DSSAT family as CROPGRO. CERES-Maize derives daily rates of crop growth (PGR, g plant^{-1} d^{-1}) as the product of light intercepted by the canopy (IPAR, MJ plant^{-1} d^{-1}) and radiation use efficiency (RUE, g MJ^{-1}). The rate of development in CERES-Maize is controlled by temperature (growing degree days: GDD). The number of GDD that accumulate on a given calendar day is based on daily maximum and minimum temperatures and is a triangular function of trapezoidal function that is defined by a base temperature, a couple of optimum temperature, and a maximum temperature. Day length sensitivity is a cultivar-specific input that can influence the total number of leaves formed by modifying the length of certain growth phases. Leaf area expansion is controlled by GDD and nitrogen and water stresses. Daily plant growth is calculated by converting intercepted PAR into plant dry matter with a crop-specific radiation-use efficiency parameter.

The CROPGRO-Soybean model is also a part of the DSSAT model and was used to calculate soybean yield in response to combined changes in precipitation, temperature, and atmospheric CO_2 concentration. CROPGRO-Soybean is a predictive and deterministic model which simulates physical, chemical, and biological processes in the plant and its associated environment. The model simulates crop yields as a function of weather, soil, and crop management conditions. Crop development in the model is differentially sensitive to temperature, photoperiod, water deficit, and nutrient stresses during various growth phases and is expressed as the physiological days per calendar day (PD d^{-1}).

2.2 Baseline climate data and climate change scenarios

Historical 10-year daily observed climate data from 1981 to 1990 for the station were used in this study. Farm level management practices with most optimal yield were chosen for the corn cultivar, McCurdy 84aa, and soybean cultivar, PIO332. Simulations were run under rain-fed conditions. Table 1 depicts the climate variables used in the generation of the climate change scenarios. Here, we used the 'environmental modification' section of the XBuild module in DSSAT-CSM model to generate climate change scenarios using variable combinations of temperature, precipitation, and atmospheric CO_2 levels. Daily changes in the climate variables were applied to the observed daily climate records. Projections were made throughout the crops growing season.

2.3 LCA analysis: GHG emissions calculation

The GHGs (kg CO_2-eq. ha^{-1} yr^{-1}) for CO_2, N_2O, and CH_4 emissions were calculated using a life cycle approach. This methodology was used to analyse the carbon footprint of whole corn bioethanol and stover biomethanol, and whole soybean biodiesel and stalk biomethanol via biomass-integrated biomethanol synthesis system. Bioethanol, biodiesel, and biomethanol were compared with petroleum-based fossil fuels according to ISO 14044 standard (ISO 2006). This method advocates the system boundary expansion method – 'displacement method' or 'substitution method' for LCAs (Börjesson and Tufvesson 2011) – Fig. 1. Models were developed using the GaBi v4.4. The crop yields are based on simulated model outputs from the DSSAT-CSM model and were used as inputs for the LCA models. In this study, average energy crop yields over 10 years were taken to smooth out annual variations due to temperature and precipitation differences. The LCA steps are described in the subsequent sections.

2.3.1 System boundary and functional unit

The system boundary in this study as shown in Fig. 1 included energy crop (feedstock) production and transportation, biofuels processing, and biofuels distribution to service station. Direct land use (transformation from set-aside to cultivated land for biofuels production) was included in the analysis, and crop farming activities such as planting, seeds, application of herbicides, harvesting, and fertilisers were also included. The importance of including land-use change emissions in the GHG balance of biofuels was highlighted by Searchinger et al. (2008) and Fargione

Table 1 Climate change parameters range and values used in the creation of climate change scenarios

Climate parameters	Values
Daily maximum temperature	+2.0, +3.0, +4.0, and +5.0 °C
Daily minimum temperature	+2.0, +3.0, +4.0, and +5.0 °C
Precipitation	+20, +10, +5, −20, −10, and −5 %
Atmospheric carbon dioxide (CO_2) concentration	+70, +210, and +350 ppm

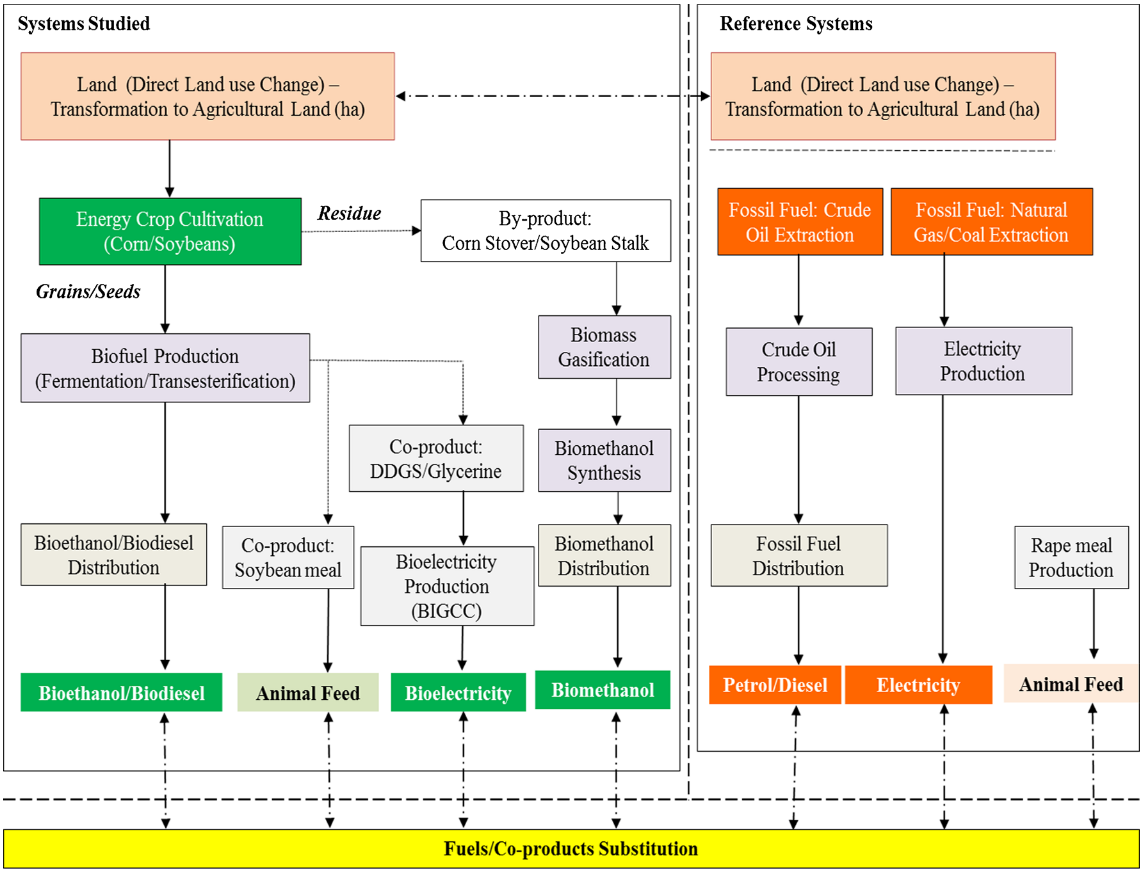
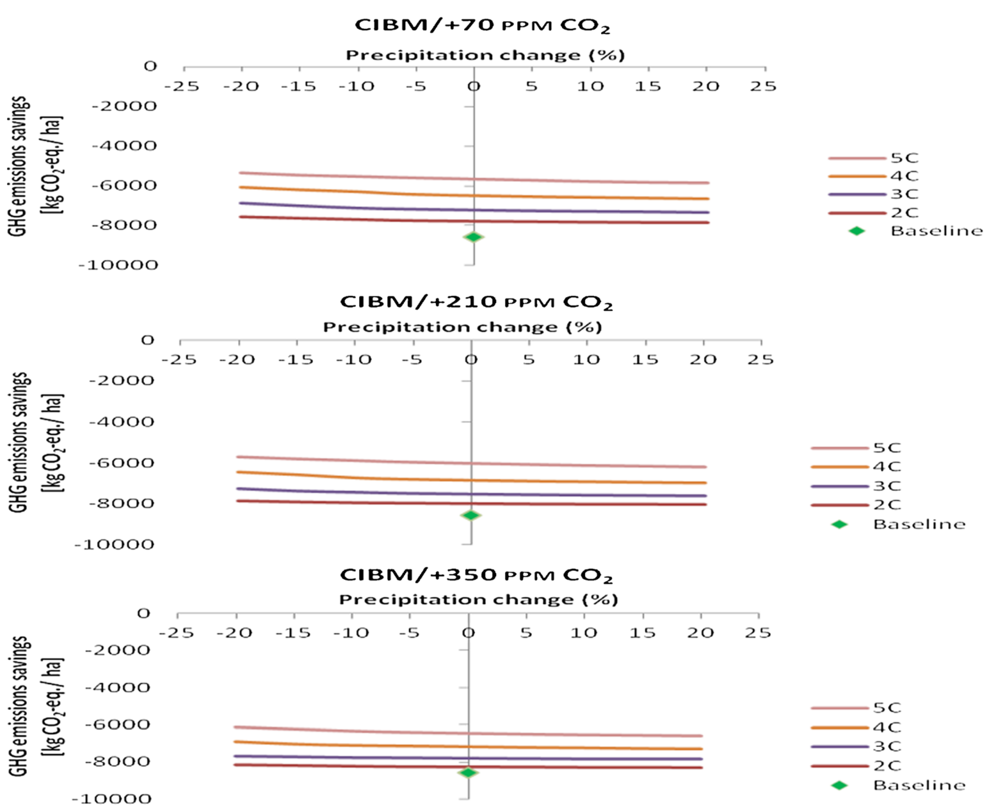


Fig. 1 System description/system boundaries for CIBM and SIBM substituting fossil-based fuels

Fig. 2 Impact of climate variables on GHG emissions savings of CIBM under baseline and climate change scenarios



et al. (2008). Upstream activities such as manufacturing of equipments/machines and chemicals were taken into account. The average 100-km feedstock transportation data were considered in the study (González-García et al. 2010).

2.3.2 Life cycle inventory (LCI)

The models representation of the physical processes inventory for the corn-integrated biomethanol synthesis (CIBM) and soybean-integrated biomethanol synthesis (SIBM) systems was constructed in GaBi v4.4 LCA software using ecoinvent v2.0 database unit process raw data that have been incorporated into the software. The datasets were preferentially selected from the USA (based in the USA) which represents the study site. However, limited availability of data has always been one of the critical issues in LCA studies, where data are not available: Data from RER (based in Europe) and the CH (Europe specific) were used in the analysis.

2.3.3 Life cycle impact assessment (LCIA)

The cumulative impact assessment results from ecoinvent (LCIA) for GHG global warming potential (GWP) were taken by applying the CML2001, 100 years global warming potential (GWP) methodology (Renó et al. 2011), due to its relevance to current legislative goals (IPCC 2007a, 2007b). Our analysis accounts for the GHG emissions from energy crops cultivation (farm operations), biofuel conversion process, and distribution to regional storage (Eq. 1).

$$GHG_{\mathrm{biofuels}} = GHG_{\mathrm{farm}} + GHG_{\mathrm{process}} + GHG_{\mathrm{distrib.}} \tag{1}$$

2.3.4 GHG emissions reduction due to fossil fuels replacement

GHG emissions reduction (GHG emissions savings) from fossil fuels displacement due to the use of biofuels was calculated as the difference between emissions from the production, distribution, and combustion (use) of their fossil fuel reference systems and the crop cultivation, production, and distribution of the biofuels (Eq. 2).

$$GHG_{\mathrm{savings}} = \left(GHG_{\mathrm{fossilprod}} + GHG_{\mathrm{fossildist}} + GHG_{\mathrm{fossilcomb}}\right) - \left(GHG_{\mathrm{biofuel}}\right) \tag{2}$$

where $GHG_{\mathrm{fossilprod}}$, $GHG_{\mathrm{fossildist}}$, and $GHG_{\mathrm{fossilcomb}}$ are the fossil-derived GHG emissions from fossil fuels production (including extraction of crude oil), fossil fuel extraction, and combustion of the displaced fossil fuel equivalent

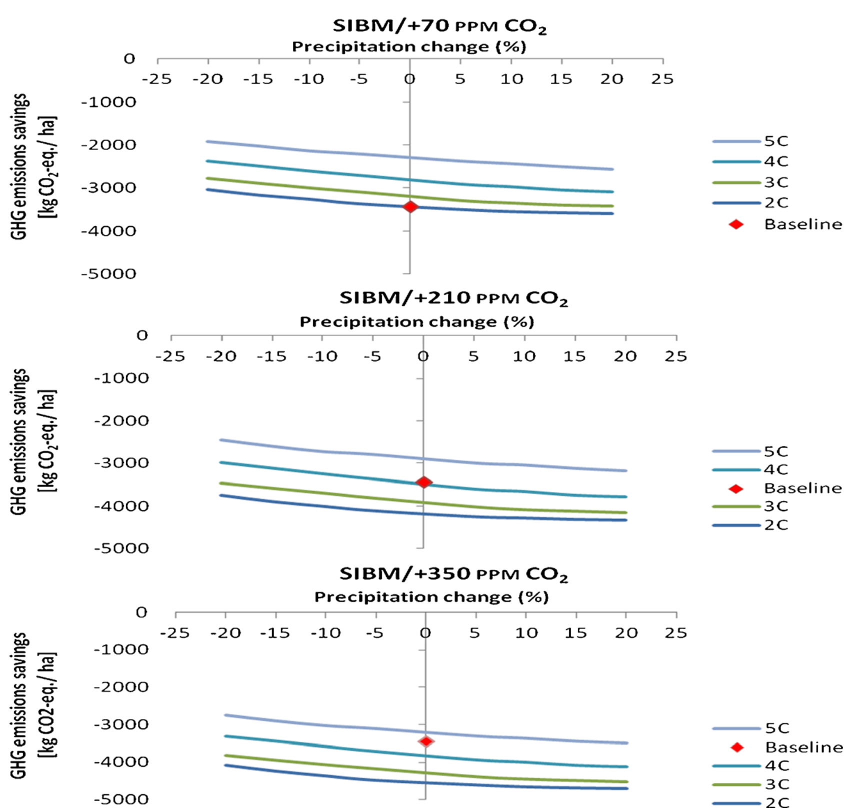


Fig. 3 Impact of climate variables on GHG emissions savings of SIBM under baseline and climate change scenarios

($fossil_{equiv.}$), which is the amount (kg) of the displaced fossil reference system defined as

$$GHG_{\text{fossilequiv.}} = biofuel_{\text{produced}} \times S_{\text{r}} \quad (3)$$

where $biofuel_{\text{produced}}$ is the amount of biofuel produced per hectare and S_{r} is the substitution ratio between the biofuel and the conventional fossil fuel (Eq. 4).

$$S_{\text{r}} = \frac{CV_{\text{biofuel}}}{CV_{\text{fossilfuel}}} \quad (4)$$

where $CV_{\text{biofuel,}}$ is the calorific value of the biofuel produced (MJ/kg) and $CV_{\text{fossilfuel}}$ is the calorific value of the displaced fossil reference system (MJ/kg).

3 Results and discussion

Production of CIBM and SIBM systems were compared with conventional fossil-based reference systems. Corn grain bioethanol and corn stover/soybean stalk biomethanol were compared with conventional gasoline (Nguyen et al. 2007; Nguyen et al. 2008), and soybean biodiesel was also compared with conventional petroleum diesel (McCormick 2007) based on their energy contents. The bioelectricity produced from co-products was compared with fossil-based electricity supply. Fuel substitution ratios of 0.5225, 0.62033, and 0.88069 were calculated when biomethanol, bioethanol, and biodiesel substitutes for gasoline and diesel, respectively. Soybean meal produced as a by-product of biodiesel production was considered to be used as animal feed, as a substitute for rape meal (Hoffman and Baker 2011; Frondel and Peters 2007). The models calculate the net GHG emissions savings from each system under current – baseline climate scenario and projected climate change scenarios.

Under current baseline climate condition, net GHG emissions savings per hectare from CIBM and SIBM were calculated as −8,573.31 and −3,441 kg CO_2-eq. ha^{-1} yr^{-1}, respectively. This indicates that huge potential for GHG emissions savings exists for the all the production systems studied. Our modelling results are in good agreement with published data from Gelfand et al. (2013) and Larson (2006) who reported GHG emissions savings capacity of −4,290 and about −4,900 kg CO_2-eq. ha^{-1} yr^{-1}, respectively, from corn when grown on marginal land in the US Midwest and Larson (2006) who also reported about −2100 kg CO_2-eq. ha^{-1} yr^{-1} potential GHG emissions savings from soybean.

Figures 2 and 3 show the calculated changes in net GHG emissions savings for CIBM and SIBM, respectively, under projected climate change scenarios. The changes in net GHG emissions savings per hectare for CIBM as illustrated in Fig. 2 are mainly due to projected changes in climate conditions. Net GHG emissions savings for CIBM decreased significantly under all projected climate change scenarios even with the direct effects of CO_2. However, increased atmospheric CO_2 concentration tends to reduce the combined effects of increased temperature and changing precipitation, thus increasing the net GHG emissions savings.

For SIBM, changes in net GHG emissions savings under projected climate change scenarios vary with scenario (i.e. combination of climate variables). Generally, as depicted in Fig. 3, net GHG emissions savings for SIBM would decline with warming (for all temperatures assessed) only at 400 ppm (+70 ppm) atmospheric CO_2 concentration. In some scenarios, the effect of increased atmospheric CO_2 concentration significantly increased the net GHG emissions savings, under climate change, higher than that of the current baseline scenario. Thus, in this study, potential beneficial effect of climate change is shown by SIBM under some projected climate scenarios.

The decrease in net GHG emissions savings per hectare for both CIBM and SIBM was mainly driven by increased air temperatures, which caused significant decrease in the harvestable grain/seed and biomass yields of the cultivated crops. Unlike SIBM, CIBM shows very little or no response to percentage changes in precipitation. Physiological effects of CO_2 caused a significant increase in the net GHG emissions savings per hectare for both CIBM and SIBM. In the case of SIBM, net GHG emissions savings per hectare increases under some projected climate change scenarios were probably due to combined effects of CO_2 fertilisation, due to increased atmospheric CO_2 levels, and increase in precipitation. The calculated changes in the net GHG emissions savings per hectare suggest that SIBM production would be equally well, if not better, in a warmer (at temperatures increase of less than +5 °C) and CO_2-enriched future climate coupled with increased precipitation. This might not be unconnected with the photosynthetic advantage that the soybean (a typical C3 crop) has over corn (a typical C4 crop) at considerably high temperatures and elevated atmospheric CO_2 than today's condition (Oliver et al. 2009).

4 Conclusions

Model calculations under current, baseline climate suggest that huge potential benefit for GHG emissions savings could be achieved from corn and soybean when second generation biomethanol production system is considered. The calculated projected changes in GHG emissions savings under climate change scenarios also suggest that advanced biomethanol production may be significantly affected by changing climate. Future possible changes in climate variable (air temperature,

precipitation, and CO_2) are important factors in determining crop yields and the resulting GHG emissions savings of biofuels. Changes in the net GHG emissions savings largely depend on crop type and climate scenario. The corn biomethanol production system was most negatively affected by climate change in all projected climate change scenarios even with the physiological effect of atmospheric CO_2. The soybean biomethanol production system significantly responded to increased atmospheric CO_2 and was positively affected by climate change under some projected climate change scenarios.

In general, biofuels production appears to be at risk, and measures should therefore be taken in choosing which crop to grow and under what condition in a changing climate when considering large-scale biofuels production system.

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